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The Practical Impacts of RTD and Thermometer Design on Wet and Dry Bulb Relative Humidity Measurements

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THE PRACTICAL IMPACTS OF RTD AND THERMOMETER DESIGN ON WET AND DRY BULB RELATIVE HUMIDITY MEASUREMENTS.

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ABSTRACT

Identification of differences in the wet and dry bulb temperatures in field conditions for different temperature sensor designs resulted in this study of wet bulb sensors. Analysis of laboratory tests in an environmental chamber resulted in two possible models for the psychrometer coefficient for these sensors. The first model included the "wet potential", that is a coefficient for the ratio of the wet bulb temperature divided by the wet bulb depression. The second model also included coefficients for wet, dry and the theoretical wet bulb depression. Both models explained a significant proportion, approximately 90% and 99% respectively, of the observed discrepancies.

INTRODUCTION

The measurement of relative humidity (RH) is critical to the day to day operation of the Bureau of Meteorology. It is fundamental in the forecasting of fog and fire weather conditions and in predictions of dew and frost for farmers. For these uses alone the measurement of relative humidity needs to be both accurate and reliable.

The Bureau uses either the traditional psychrometric method of wet and dry bulb temperature measurements or the more modern capacitance probe technology. Generally the Bureau uses the psychrometric method wherever it has people available to maintain the equipment and uses the capacitance technology at remote stations. The accuracy of psychrometric measurements of relative humidity are dependent on a number of factors including the accuracy, shape and stem correction of the sensor and the air flow around the sensor.

The Bureau uses a number of different types of temperature sensor for measurement of relative humidity. This includes both mercury-in-glass thermometers and platinum resistance sensors (RTD). There has been concern about the comparability of these sensors. However it has generally been assumed that any differences are small in the context of field measurement. The aim of this paper is to investigate the truth of this assumption.

LABORATORY EXPERIMENTAL

The study can be broken up into two components. Laboratory studies of the psychrometric properties of the four commonly used wet bulb sensors and, results of field comparisons of platinum resistance sensors and mercury-in-glass thermometers.

Four different types of temperature measuring devices were studied in these tests. Two different RTDs of Bureau design, a Dobbie Assman type mercury-in-glass thermometer and an ordinary mercury-in-glass thermometer that conformed to the design criteria of AS2819 [1]. The *ordinary* mercury-in-glass thermometer has a spherical bulb approximately 10 mm in diameter. The *Assman* thermometer has an elongated bulb 18 mm long and 4 mm in diameter. The two RTD designs are constructed of stainless steel with a long shaft and a connector at the top. The *original* design had a 6mm diameter and 75 mm long shaft with a cannon connector approximately 60mm long and 30mm in diameter. The newer RTD (*Slim*) design consists of a shaft 4 mm in diameter and 150 mm long with a Lemo connector approximately 60 mm long and 22 mm in diameter.

Seven sensors, two ordinary and one Assman thermometers, two original and two Slim RTDs, plus two reference dry bulb sensors were cleaned and mounted in an Hereaus 4010 Environmental Chamber. The conditions in the chamber varied from 10 to 95 %RH over the range of temperatures 10 to 50 °C. A General Eastern Chilled Mirror Hygrocomputer Model 1500 (S.N 3415 and 3416) was used as the reference for the dew point. An Instrulab Model 4312A (s/n 30077) was used to measure the resistance of the RTD under test. Two high precision Instrulab RTDs (s/n 947 and 948) were used as the dry bulb reference.

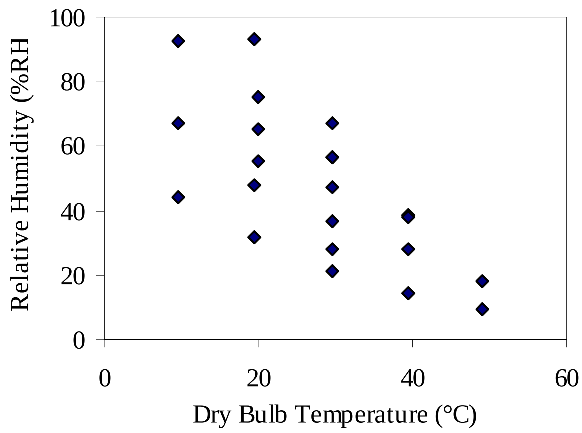

Figure 1 Conditions the wet bulb sensors were tested under.

23 different conditions were tested (see Figure 1) and each sensor was measured 6 times at a condition. A minimum of an hour was allowed between sets of measurements for the chamber and the wet sensors to come to equilibrium.

The stem correction for each of the sensors was determined by measuring the temperature of the sensor when fully emersed in oil and again when the sensor was emersed to the same level the wick would cover the element in normal operation. The difference between the temperatures was taken to be the stem correction at that temperature. Each probe was checked at oil bath temperatures of 13 and 3 °C and an ambient temperature of approximately 23 °C. This simulated a wet bulb depression of 10 and 20 °C. For this study the stem correction was assumed to be constant for a particular wet bulb depression.

FIELD STUDIES

At sites such as Wagga Wagga, Melbourne, Tennent Creek, Mildura, Cape Grim and Esperance comparisons of the original RTD or Slim RTD and ordinary mercury-in-glass thermometers were carried out as a routine function of the station. The wet and dry bulb temperatures for two sets of instruments housed in the one temperature screen were recorded for each station. At a number of sites discrepancies between the RTD psychrometric readings and the ordinary mercury-in-glass thermometers were observed. Results of these comparisons for Wagga Wagga, Melbourne and Esperance are given in Figure 2.

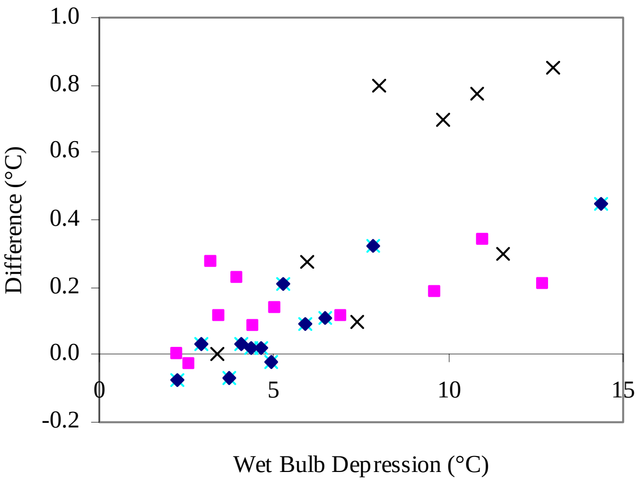

Figure 2 Plot of mean differences between the wet bulb depression measured by RTDs and oridinary thermometers at Melbourne (squares), Esperance (diamonds) and Wagga Wagga (crosses).

From Figure 2 it is clear that there is a trend in the difference between the mercury-in-glass thermometer and RTD measurements of relative humidity. The ordinary mercury-in-glass measurement results in higher wet bulb temperatures and therefore smaller wet bulb depressions. Early interpretations of similar data had blamed the difference on the stem correction of the original RTD. As a result the probe was redesigned to minimise such errors and resulted in the Slim probe, which has a stem correction of < 0.05 °C. However the Slim probe, which was installed at Wagga Wagga, demonstrated the same or worse differences. To resolve this issue the various sensors were tested under controlled conditions in an environmental chamber.

LABORATORY STUDIES

Figure 3 is a plot of the correction of the wet bulb depression for each of the sensor types to the calculated wet bulb depression against the reference relative humidity. The wet bulb depression, W_d, was calculated using the World Meteorological Organization (WMO) recommended psychrometer equation [2], [3]. The typical uncertainty for the data is ±0.09 °C. The reference relative humidity was calculated from the dew point measured by the cold dew mirror.

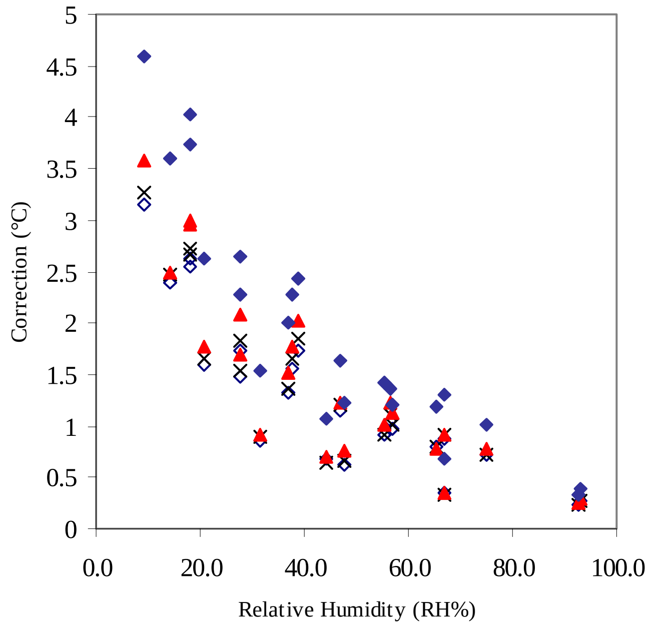

Figure 3 Correction of wet depression to the theoretical wet bulb depression at a given relative humidity. Slim RTD (Open Diamond), Original RTD (Cross), Assman (Triangle) and Ordinary thermometer (Diamond)

The equations [2] used to calculate the relative humidity, U, are given below, where $e'_w(p, y)$ is the saturation vapour pressure of moist air with respect to the water at temperature y and pressure p, f(p) is the

Goff-Grach factor, $e_w(y)$ is the saturation vapour pressure in the pure phase with respect to water at temperature y and t, t_w and t_d are the dry wet and dew point temperatures respectively.

$$U = 100\, e'_w(p,t_d) / e'_w(p,t) \quad (1)$$

where

$$e'_w(p,y) = f(p) * e_w(y) \quad (2)$$

$$e_w(y) = 6.112 \exp [17.62\, y / (243.12 + y)] \quad (3)$$

$$f(p) = 1.0016 + 3.15*10^{-6}\, p - 0.074 / p \quad (4)$$

It is clear from Figure 3 that for each of the sensors the error in the wet bulb measurement increases as the web depression increases or the relative humidity decreases. However for the ordinary mercury-in-glass the error is significantly worse, especially at low relative humidities. This, in part, can be attributed to the stem correction for the thermometer, which is of the order of -0.3 °C.

Theoretical Estimations of Relative Humidity

For each sensor the relative humidity was estimated using the WMO recommended psychrometer coefficient (see equation (5)) for an Assman psychrometer [2], [3]. It is recognised that the test conditions do not perfectly emulate those of an aspirated Assman psychrometer. However the conditions are similar and the equation is of the same form as that used in Bureau automatic weather stations to calculate relative humidity.

$$A = 6.53*10^{-4} (1 + 0.000944\, t_w) \quad (5)$$

Using this, the mean difference between the relative humidity measured by the cold dew mirror and the relative humidity as measured by the various sensors varied between 5 and 2 %RH higher than expected. The results are given in Table 1.

Polynominal Model for A_e

To start to identify the reason for the observed discrepancies a number of models for the psychrometer coefficient were determined. The simplest involved a straight forward fifth order polynomial fit to an estimation of A, A_e. The latter was estimated by inverting the psychrometer equation (6) for vapour pressure e'.

$$A_e = (e'_w(p,tw) - e') / (p\,(t-t_w)) \quad (6)$$

This reduced the overall bias significantly but did not account particularly well for the overall uncertainty (see Table 1) . Most significantly this model did not account for the deviations from the expected values at high and low relative humidity.

	Hg	**Assman**	**Original**	**Slim**
Theoretical				
Bias %RH **(U_{95}) %RH**	-5.03 (0.59)	-2.59 (0.25)	-2.12 (0.18)	-1.97 (0.19)
Polynomial				
Bias %RH **(U_{95}) %RH**	0.10 (0.33)	0.16 (0.36)	0.12 (0.27)	0.09 (0.21)
Bias Reduced **(U_{95}) Reduced**	98% (44%)	94% (-44%)	94% (-47%)	95% (-11%)
Wet Potential				
Bias %RH **(U_{95}) %RH**	-0.59 (0.32)	-0.38 (0.30)	-0.09 (0.24)	0.07 (0.21)
Bias Reduced **(U_{95}) Reduced**	88% (45%)	85% (-20%)	96% (-29%)	96% (-10%)
Multi Factor				
Bias %RH **(U_{95}) %RH**	0.06 (0.24)	0.02 (0.12)	0.02 (0.09)	0.03 (0.09)
Bias Reduced **(U_{95}) Reduced**	99% (59%)	99% (53%)	99% (48%)	99% (51%)

Table 1 The mean bias and uncertainty in the mean bias between the reference relative humidity and the relative humidity determined using the four models. The bias and U_{95} is expressed in %RH. The bias reduced and U_{95} reduced are indications of the percentage reduction in the bias and U_{95} achieved using the three alternate models.

Wet Potential Model for A

The second model used both the wet bulb temperature and the wet bulb depression (see equation (7)).

$$A = C_1 * t_w / (t - t_w) + B \quad (7)$$

It was hypothesised, that since the greatest errors were observed at low relative humidity and in the sensor which had the lowest surface to volume ratio 0.2, that the error was related to the evaporation potential and efficiency of the wet bulb device. Therefore a linear fit of the data to the wet bulb temperature, wet bulb depression and the ratio of wet bulb temperature to the wet bulb depression were tried. The latter proved to be the most reliable model for all four sensor types. The results for the residuals for this model are given in Table 1.

This model reduced the mean bias observed between the experimental data and the model data. It was particularly effective for the RTD sensors reducing the overall difference by 96% from approximately 2 %RH to 0.1 %RH. The bias for the mercury-in-glass thermometer was not reduced as much by this model as the polynomial model. However the wet potential model results in either a slight reduction or significantly less increase in the uncertainty than the polynomial model for all sensors.

Multi-Factor Model for A

A number of attempts to refine the model were made by including various combinations of the dry bulb temperature, wet bulb temperature and wet bulb depression. However the only model that improved the fit and was statistically significant included the dry and wet bulb temperatures and the expect value for the wet bulb depression, W_d. This was calculated using equation (8). The resultant equation for the psychrometer coefficient is given in equation (9).

$$W_d = [e'_w (p, t_w) – U / (e'_w (p, t) * 100)] / [(6.53 . 10^{-4} . (1 + 0.000944 t_w) p] \quad (8)$$

$$A = C_1 * t_w / (t – t_w) C_2 * t + C_3 * tw + C_4 . W_d + B \quad (8)$$

This model of the psychrometer coefficient reduces the difference between the experimental data and the model values by 99% for all the sensors (see Table 1). It also reduces the uncertainty by approximately 50% for all sensors. Interestingly the model is very sensitive to the values used for the expected wet bulb depression. The use of corrected experimental wet bulb depressions instead of the theoretical value failed to provide satisfactory results.

Comparison of Models

Figure 4 shows the coefficients for the wet potential model and the multi factor model for the four different types of sensor used. As can be seen the values for the coefficient of $t_w/(t-t_w)$, C_1, and the constant change very little between the two models. However the standard error of the fit to the data improves significantly. The coefficients for the dry and wet bulb are nearly equal in magnitude but of opposing signs. This is, theoretically, the equivalent of using the measured wet bulb depression however a slightly better result is achieved using the individual wet and dry bulb temperatures. This is likely to be because the absolute dry bulb temperature influences the evaporation rate water off the wick. Inclusion of the dry bulb temperature appears to force a stronger waiting in the fit to the actual wet bulb depression than the than use of the wet bulb depression itself does. This is reflected in a reduction in the waiting given to the theoretical wet bulb depression.

Figure 5 is a plot of the corrections to relative humidity for each model against the reference relative humidity. The plot is of data for the ordinary mercury-in-glass thermometer only, however the results for the other sensors are similar. This demonstrates the described reduction in both the mean bias and uncertainty in the bias.

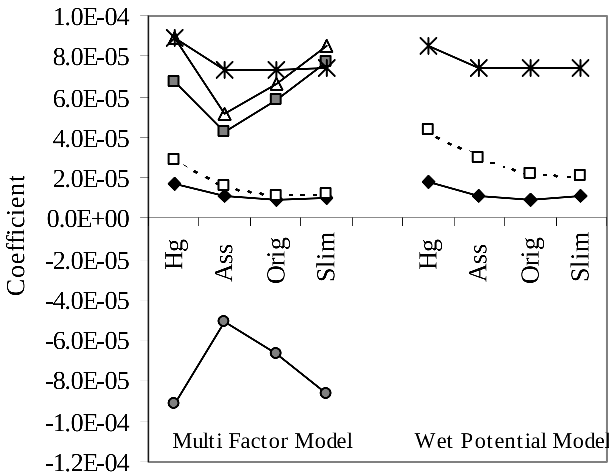

Figure 4 Model coefficents for each sensor type. (diamonds = wet potential C1, circles = dry bulb C2, triangles = wet bulb C3, squares = theoretical wet bulb depression C4, stars = constant B and open squares = standard error of the fit)

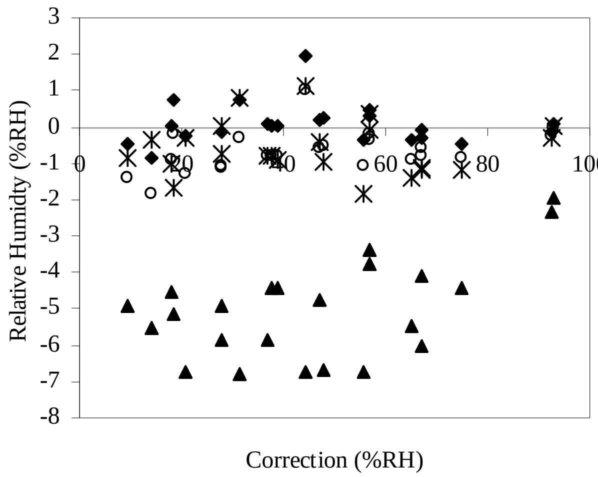

Figure 5 Reference relative humidity verses the correction in relative humidty for the ordinary mercury in glass thermometer (triangles = theoretical model, circles = wet potential model, diamonds = multi factor model and stars = multi factor model without stem correction)

The multi factor model explains more of the uncertainty in the mean by removing a dry bulb related bias. Figure 6 is a plot of the bias in the relative humidity of the reference and the model estimate of relative humidity for each model against the dry bulb temperature. The data shown is the results for the ordinary mercury-in-glass thermometer. Results for the other sensors are similar. It is clear from this figure that the significant difference at high dry bulb temperatures is only partly reduced by the wet potential model and requires both the measured and the theoretical wet bulb depression to eliminate it completely.

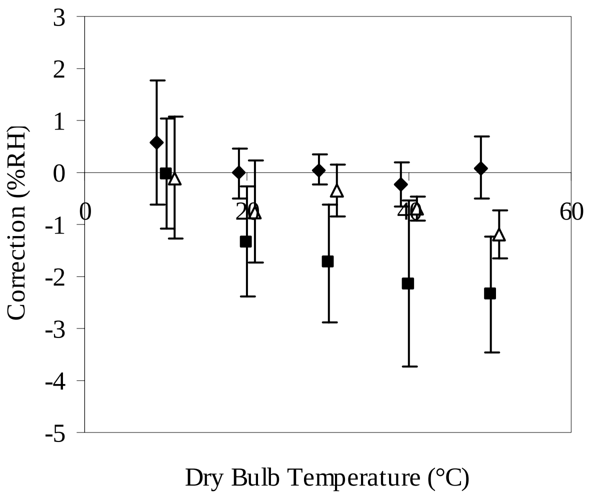

Figure 6 Dry bulb temperature verses the correction the relative humidity for the three models. (squares = theoretical model, triangles = wet potential model, diamonds = multi factor model)

Stem Correction

Thus far through this paper the wet bulb temperatures used have been corrected for the stem correction determined in the laboratory. Figure 5 shows both the stem corrected and uncorrected relative humidity biases for the multi factor model. This and Table 2 show that the error removed by applying these stem corrections is relatively small, between 0 and 20 %. This is significantly less than initially expected but agrees with the field observation that removal of the stem correction by introduction of the Slim design did not greatly change the observed performance of psychrometer measurements in the field (see Figure 1)

	Hg	Assman	Original	Slim
Bias %RH	-0.74	-0.52	-0.22	-0.03
U_{95} %RH	0.11	0.08	0.03	0.00
	13%	20%	9%	0%

Table 2 The mean bias between the estimate of relative humidity using the multi factor model with and without stem corrections.

CONCLUSION

It is clear from this study that the performance of these thermometer designs falls well short of the theoretically perfect psychrometer sensor [4]. This is despite the fact that the Slim sensor is very similar in design to the RTDs used in the Wylie psychrometer. The worst of the sensors is the ordinary mercury-in-glass thermometer. The spherical bulb and therefore low surface to volume ratio means that evaporation of this surface is poor and results in the sensor being less sensitive to the environmental conditions it is designed to measure. Both the models for the psychrometer coefficient presented in this paper support this conclusion, as they both produce significantly larger wet potential coefficients, C_1, for the ordinary thermometer than the other sensors tested. All the other sensor designs have much larger surface area to volume ratios and similar model results for the wet potential coefficient and constant. This indicates that beyond a particular point the design of the sensor has little impact on the wet potential.

It is not clear from this work why both the measured wet bulb depression and a theoretical estimate of the depression are required to model the relative humidity response accurately. The need for the theoretical wet bulb depression is a weakness in the model as it requires the true relative humidity to be known before a satisfactory value of A can be determined. What is does indicate is that the sensors are sensitive to other parameters not included in this study such as the diameter of the bulb, radiation and air flow. The latter is the most likely source of error as models for A generally assumes laminar flow. In these experiments the flow was turbulent. Further work will be required to resolve this issue.

Importantly both the models removed the significant error correlated with the dry bulb temperature. From this work it would seen reasonable to use a wet potential model as a first order improvement to the theoretical model currently used. It is likely that the deviation in the behaviour of the sensors is due to turbulent flow around the elements instead of the laminar flow assumed by may psychrometer models. Further work is required to resolve this and the theoretical wet bulb depression issue.

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